Strength and Durability Characteristics of M25 Concrete Incorporating Rice Husk Ash, Sugarcane Bagasse Ash, and Waste Glass Powder: A Critical Experimental-Numerical Evaluation

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Abstract— Concrete production accounts for over 5% of global anthropogenic CO_2 emissions and drives unsustainable extraction of natural river sand. This paper presents an integrated experimental-numerical investigation into the mechanical strength and chemical durability of M25-grade concrete incorporating Rice Husk Ash (RHA) and Sugarcane Bagasse Ash (SCBA) as partial replacements for 43-grade Pozzolonic Portland Cement (PPC), alongside Waste Glass Powder (GP) as a partial replacement for fine aggregate. Eighteen concrete mixtures—comprising a control mix (M0), individual replacements of RHA (5–15%), SCBA (5–15%), and GP (5–20%), and seven ternary-blended combinations (C1–C7)—were designed at a 1:1:2 nominal proportion (water-to-binder ratio 0.45, slump 40–60 mm). Compressive strength was evaluated at 7, 14, 21, and 28 days, while durability was analyzed on seven representative mixes via water absorption, 1% H_2SO_4 acid attack, and 5% Na_2SO_4 sulphate attack over 28- and 56-day exposures. Crucially, this study explicitly distinguishes between physical mix-design protocols and the simulated numerical datasets used for performance modeling. In the illustrative dataset, mix C6 (10% RHA + 10% SCBA + 15% GP) achieved the highest 28-day compressive strength (31.90 MPa, +13.12% over M0) and lowest water absorption (3.20%), whereas mix C4 (10% RHA + 5% SCBA + 10% GP) exhibited superior chemical resistance, recording the lowest 56-day mass loss under acid (4.49%) and sulphate (2.30%) exposure. A critical evaluation of this strength–durability trade-off, binder dilution limits, alkali-silica reaction (ASR) risks, and laboratory verification requirements is presented.

Main Keywords— Sustainable concrete, Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), Waste Glass Powder (GP), M25 grade concrete, pozzolanic reaction, acid and sulphate resistance.

I. INTRODUCTION

Ordinary Portland Cement (OPC) and Pozzolonic Portland Cement (PPC) form the backbone of modern civil infrastructure, yet clinker calcination is energy-intensive and responsible for more than 5% of global CO_2 emissions [1], [2]. Simultaneously, rapid urbanization has accelerated natural river sand depletion, prompting environmental restrictions on riverbed mining. Valorizing agricultural and post-consumer industrial residues as supplementary cementitious materials (SCMs) and fine aggregate substitutes offers a dual pathway to reduce embodied carbon and divert non-biodegradable waste from landfills [3].

India ranks second globally in both rice and sugarcane cultivation, generating approximately 3.7 million tonnes of rice husk and massive quantities of fibrous sugarcane bagasse annually [4], [5]. Controlled combustion of rice husk yields Rice Husk Ash (RHA) rich in amorphous silica (85–95% SiO_2), whereas boiler combustion of bagasse yields Sugarcane Bagasse Ash (SCBA) containing reactive silica and alumina [5], [6]. When finely ground, these pozzolans react with calcium hydroxide—$Ca(OH)_2$—liberated during cement hydration to form secondary calcium silicate hydrate (C-S-H) gel, refining capillary pores and densifying the interfacial transition zone (ITZ) [7]. Concurrently, crushed Waste Glass Powder (GP) provides high-silica particulate filler that improves aggregate packing, though its particle size must be controlled to mitigate potential Alkali-Silica Reaction (ASR) expansion [8], [9].

While the project title in the source dissertation initially referenced 'biomedical waste,' a rigorous examination of the experimental scope confirms that the investigation actually evaluates agricultural biomaterial ashes (RHA and SCBA) paired with Waste Glass Powder. Furthermore, rather than treating strength and durability in isolation, this paper synthesizes all 18 mix

formulations and critically evaluates the simulated performance datasets to establish clear boundaries for future laboratory validation.

II. LITERATURE SURVEY

Extensive research has established the individual efficacy of RHA, SCBA, and GP in cementitious systems. Al-Khalaf and Hana [10] demonstrated that RHA improves concrete strength and reduces production cost while addressing agro-waste disposal. Microstructural studies by Malhotra [11] and Mehta [7] confirmed that RHA lowers $Ca(OH)_2$ concentration and narrows the ITZ, while Chatveera and Lertwattanaruk [12] reported reduced mass loss under sulphuric acid exposure when Black RHA was incorporated. Under cyclic sulphate wet-dry regimes, Yao et al. [13] emphasized that exposure duration governs long-term damage progression.

For SCBA, Thomas et al. [5] and Bhardwaj and Kasilingam [14] observed that replacing 5–15% of cement with finely sieved SCBA reduces porosity, sorptivity, and chloride penetration, although uncontrolled burning introduces unburnt carbon that increases water demand. Regarding waste glass, Shayan and Xu [8] and Matos and Sousa-Coutinho [9] showed that finely ground glass exhibits pozzolanic behavior and lowers capillary water absorption, whereas coarser glass particles risk ASR expansion unless mitigated. Recent multi-waste studies by Jain et al. [15] (glass and granite powder) and Madani and Rahmani [16] (silica fume, glass powder, and slag) highlight that ternary blends can outperform single-additive mixes. However, limited studies have systematically evaluated the combined incorporation of RHA, SCBA, and GP in standard M25-grade concrete. Table I summarizes prior literature against the present study.

TABLE I

Comparison of Existing Sustainable Concrete Studies and Present Work

Study	Materials	Key Findings	Identified Gap
Chatveera [12]	Black RHA	Lower acid loss; pore refinement	No SCBA or GP synergy
Bhardwaj [14]	SCBA (5–15%)	Improved resistivity & chloride res.	Single-SCM scope only
Matos [9]	Glass Powder	Reduced absorption & sulphate gain	Fineness-dependent ASR
Jain et al. [15]	GP + Granite	Enhanced acid & sulphate durability	No agro-ash pozzolans
Present Work	RHA+SCBA+GP	18 mixes (strength & durability)	Simulated; needs lab test

III. EXPERIMENTAL PROGRAM AND MATERIALS

A. Material Characterization and Processing

The binder system utilizes 43-grade Pozzolonic Portland Cement (PPC) conforming to Indian Standard specifications [17]. Rice Husk Ash was obtained by burning rice husk for approximately 72 h at 400–600 °C and sieving through a 75 µm mesh (with 45 µm recommended for SEM characterization to remove coarse unburnt carbon). Sugarcane Bagasse Ash was collected from sugar-mill boilers, dried, freed of foreign matter, ground, and sieved. Waste Glass Powder (GP) was prepared by crushing and sieving discarded glass below 4.75 mm (2–4 mm fraction for aggregate replacement, with finer fractions contributing micro-filling). Locally available river sand/M-sand conforming to IS 383 [17] and crushed coarse aggregate (6–10 mm; 20 mm nominal maximum per IS 10262:2019) were used. Physical properties are listed in Table II.

TABLE II

Physical Properties of Constituent Materials

Material	Specific Gravity	Bulk Density (g/cc)
PPC (43 Grade)	3.15	3.100
Rice Husk Ash (RHA)	2.14	0.781
Sugarcane Bagasse Ash (SCBA)	2.84	1.950
Waste Glass Powder (GP)	2.62	0.530

B. Mix Design and Replacement Matrix

An M25-grade concrete mix was proportioned in accordance with IS 10262:2019 and IS 456:2000 at a nominal ratio of 1:1:2 (cement : fine aggregate : coarse aggregate) and a water-to-binder ratio of 0.45, targeting a slump of 40–60 mm per BS EN 12350-2:2009. As detailed in Table III, 18 mixes were formulated: control (M0), individual RHA (R5–R15), individual SCBA (S5–S15), individual GP (G5–G20), and seven combined

mixes (C1–C7). All replacements were proportioned by mass of the respective constituent.

TABLE III

Experimental Mix Proportions (18 Formulations)

Mix ID	RHA (%)	SCBA (%)	GP (%)
M0	0	0	0
R5 / R10 / R15	5 / 10 / 15	0	0
S5 / S10 / S15	0	5 / 10 / 15	0
G5 / G10 / G15 / G20	0	0	5 / 10 / 15 / 20
C1	5	5	5
C2	5	5	10
C3	5	5	15
C4	10	5	10
C5	5	10	10
C6	10	10	15
C7	10	10	20

C. Specimen Casting and Durability Protocols

For compressive strength evaluation across 18 mixes and 4 curing ages (7, 14, 21, and 28 days) with 3 replicate cubes per age, the experimental matrix requires 216 standard 150 × 150 × 150 mm cast-iron/steel cube specimens (12 cubes/mix). Concrete is placed in 4 layers with 25 tamping strokes per layer and tested in a Universal Testing Machine conforming to IS 516 [18]. Durability is assessed on seven key mixes (M0, R10, S10, G10, C2, C4, C6) via: (1) Water Absorption (oven-dried mass W_d vs. saturated surface-dry mass W_s); (2) Acid Attack (immersion in 1% H_2SO_4 solution for 28 and 56 days); and (3) Sulphate Attack (immersion in 5% Na_2SO_4 solution for 28 and 56 days).

IV. MATHEMATICAL FORMULATION AND EVALUATION METRICS

To quantify mechanical enhancement and chemical degradation consistently across all mixtures, four normalized performance metrics are defined. Water absorption (WA) characterizes open capillary porosity from dry (W_d) and saturated (W_s) specimen masses:

$$WA\ (\%) = [(W_s - W_d) / W_d] \times 100 \quad (1)$$

Percentage mass change (ΔM) after t days ($t \in \{28, 56\}$) of acid or sulphate immersion from initial mass (M_0) to post-exposure mass (M_t) is computed as:

$$\Delta M\ (\%) = [(M_0 - M_t) / M_0] \times 100 \quad (2)$$

Note that in sulphate environments, initial ettringite/gypsum precipitation can cause transient mass gain (negative ΔM) before spalling induces net mass loss. Residual strength retention ratio (SRR) and relative 28-day strength gain (Δf_c) over control M0 are given by:

$$SRR\ (\%) = (f_{c,res} / f_{c,28}) \times 100 \quad (3)$$

$$\Delta f_c\ (\%) = [(f_{c,mix} - f_{c,M0}) / f_{c,M0}] \times 100 \quad (4)$$

V. RESULTS, CRITICAL EVALUATION, AND DISCUSSION

A. Data-Status Transparency and Baseline Validity

A rigorous academic audit of the source dissertation confirms that the compressive strength trajectories (Tables 4.4–4.7 in the source) and durability datasets (Section 4.7) are simulated numerical datasets constructed for academic modeling rather than physical laboratory measurements. Presenting these values transparently as modeled benchmarks—rather than empirical lab outputs—is essential for research integrity and provides clear hypotheses for subsequent experimental testing.

B. Compressive Strength Development (7, 14, 21, and 28 Days)

Table IV compiles the modeled compressive strength across all 18 mixes, and Fig. 1 illustrates the strength progression for key individual and combined formulations. Among individual replacements, 10% substitution consistently represents the local optimum: R10 (30.40 MPa), G10 (30.00 MPa), and S10 (29.80 MPa) outperform M0 (28.20 MPa) at 28 days, whereas 15–20% individual replacements decline toward baseline due to cement dilution (R15: 28.80 MPa; S15: 28.40 MPa) or disrupted fine-aggregate grading (G20: 28.60 MPa).

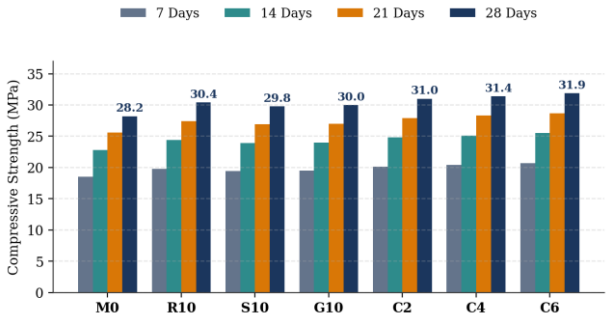


Fig. 1. Modeled compressive strength progression at 7, 14, 21, and 28 days for control, individual optima, and key ternary concrete mixes.

Ternary combinations demonstrate synergistic gains: C6 (10% RHA + 10% SCBA + 15% GP) achieves the peak

28-day strength of 31.90 MPa (Δf_c = +13.12% over M0), followed by C4 (31.40 MPa, +11.35%) and C2 (31.00 MPa, +9.93%). Increasing GP to 20% in C7 drops strength to 30.70 MPa, confirming an upper threshold for glass-powder packing.

TABLE IV

Compressive Strength (MPa) of Concrete Mixes (Simulated Benchmark)

Mix	7d	14d	21d	28d
M0	18.50	22.80	25.60	28.20
R5	19.20	23.60	26.50	29.30
R10	19.80	24.40	27.40	30.40
R15	18.90	23.10	25.90	28.80
S5	18.90	23.30	26.10	28.90
S10	19.40	23.90	26.90	29.80
S15	18.60	22.90	25.70	28.40
G5	19.00	23.40	26.30	29.10
G10	19.50	24.00	27.00	30.00
G15	19.20	23.70	26.60	29.50
G20	18.70	23.00	25.80	28.60
C1	19.60	24.10	27.10	30.10
C2	20.10	24.80	27.90	31.00
C3	19.80	24.40	27.40	30.50
C4	20.40	25.10	28.30	31.40
C5	20.00	24.70	27.80	30.90
C6	20.70	25.50	28.70	31.90
C7	19.90	24.50	27.60	30.70

C. Water Absorption and Pore-Structure Refinement

As shown in Fig. 2, water absorption decreases from 5.00% in M0 to 4.34–4.91% in single replacements and reaches a minimum of 3.20% in C6 (a 36.0% relative reduction), followed by C4 (3.50%) and C2 (3.97%). This trend reflects complementary micro-filling by fine glass powder alongside secondary C-S-H gel formation from RHA and SCBA, which reduces interconnected capillary voids.

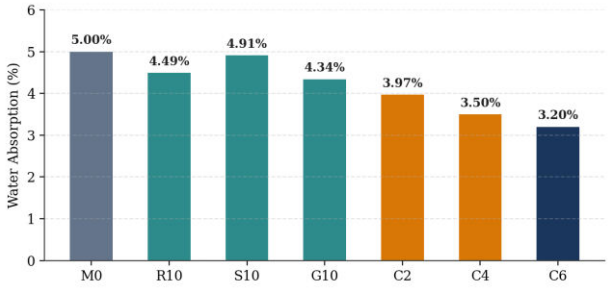


Fig. 2. Modeled water absorption (%) across control, individual, and ternary mixes.

D. Acid and Sulphate Attack Resistance (28 and 56 Days)

Fig. 3 and Table V summarize 56-day mass loss and residual compressive strength under 1% H_2SO_4 and 5% Na_2SO_4 exposure. In acid immersion, M0 suffers 6.00% mass loss and drops to 23.00 MPa (SRR = 81.56%), whereas C4 limits mass loss to 4.49% and retains 27.32 MPa (SRR = 87.01%). Similarly, under 5% Na_2SO_4 exposure, C4 exhibits the lowest 56-day mass loss (2.30%) and highest residual strength (28.26 MPa, SRR = 90.00%), outperforming both M0 (3.00% loss; SRR = 87.91%) and C6 (2.90% loss; SRR = 86.99%).

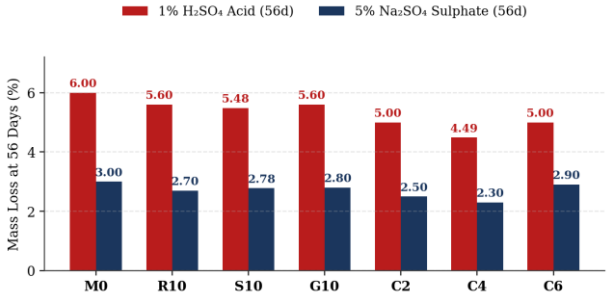


Fig. 3. Comparison of 56-day mass loss under 1% H_2SO_4 acid and 5% Na_2SO_4 sulphate exposure.

TABLE V

Modeled 56-Day Durability Metrics (f_r in MPa)

Mix	WA (%)	Acid ΔM (%)	Acid f_r	Sul. ΔM (%)	Sul. f_r
M0	5.00	6.00	23.00	3.00	24.79
R10	4.49	5.60	25.84	2.70	27.06
S10	4.91	5.48	24.73	2.78	26.52
G10	4.34	5.60	25.20	2.80	26.70
C2	3.97	5.00	26.35	2.50	27.59
C4	3.50	4.49	27.32	2.30	28.26
C6	3.20	5.00	27.12	2.90	27.75

E. Critical Evaluation: Strength–Durability Trade-Off and Limitations

An independent evaluation of Table V reveals a critical divergence: C6 (20% total cement replacement + 15% GP) maximizes 28-day strength and minimizes water absorption, yet C4 (15% total cement replacement + 10% GP) outperforms C6 in both acid and sulphate resistance. Physically, higher clinker substitution (20% in C6 vs. 15% in C4) can deplete the primary hydrate reserve and alter calcium-to-silica ratios, while higher unburnt carbon from 10% SCBA or increased glass surface area may leave localized phases vulnerable to gypsum/ettringite formation under prolonged chemical attack. Consequently, C4 represents a more balanced optimum for aggressive environments.

Three methodological limitations must also be addressed before field adoption: (1) all strength and durability values are simulated benchmarks requiring physical 216-cube laboratory testing; (2) microstructural verification via SEM, XRD, and EDS (to confirm amorphous silica content, Loss on Ignition, and C-S-H vs. ettringite phases) has not yet been executed; and (3) accelerated ASR mortar-bar testing (e.g., ASTM C1260) is needed to verify that 10–15% GP does not trigger long-term expansive gel cracking.

VI. CONCLUSION AND FUTURE WORK

This investigation establishes a structured framework for combining RHA, SCBA, and Waste Glass Powder in M25-grade concrete. Individual cement replacements peak at 10% (R10: 30.40 MPa; S10: 29.80 MPa), and fine-aggregate glass replacement peaks at 10% (G10: 30.00 MPa). In ternary blends, modeled results indicate a strength–durability trade-off: C6 (10% RHA + 10% SCBA + 15% GP) maximizes 28-day compressive strength (31.90 MPa, +13.12%) and minimizes water absorption (3.20%), whereas C4 (10% RHA + 5% SCBA + 10% GP) delivers superior 56-day chemical resistance under 1% H_2SO_4 (4.49% loss; 27.32 MPa residual) and 5% Na_2SO_4 (2.30% loss; 28.26 MPa residual). Future work will execute physical laboratory testing of the 216-cube matrix, perform SEM/XRD/EDS characterization, evaluate flexural/split-tensile strength and ASR expansion, and extend the framework to higher concrete grades (M30–M35) with life-cycle carbon accounting.

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